X-ray Microtopography:
Mapping Deformation Fields in Integrated Circuit Metallization

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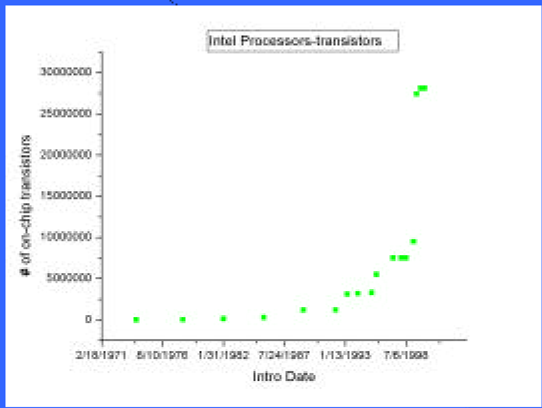
The ULSI Environment

Over the past two decades, the microelectronics industry has achieved:

- An exponential increase in the number of wireable logic circuits per chip,
- Yearly cost reductions around 20%,
- Yearly increase of 60% in the number of bits per chip.

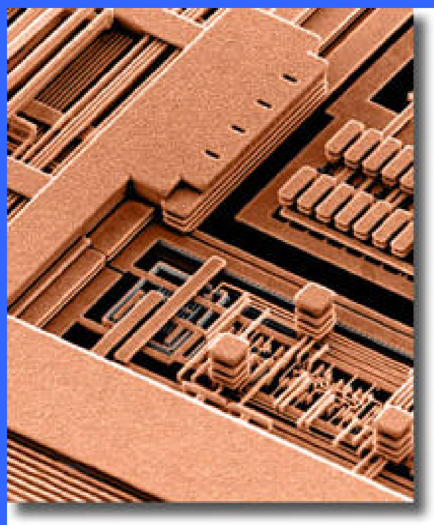


Typical failure rates are still specified at one chip per thousand manufactured!

Each chip has millions of transistors, comparable number of passive elements,

Many meters of sub-micron interconnection wire on multiple levels,

Several million vias that connect these levels.



To achieve workable devices, a large array of dissimilar materials in very small quantities are used in close proximity.

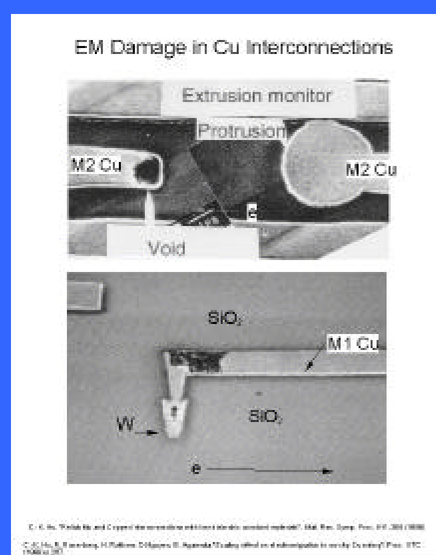
The various processes that are used to deposit these substances may not always work as expected:

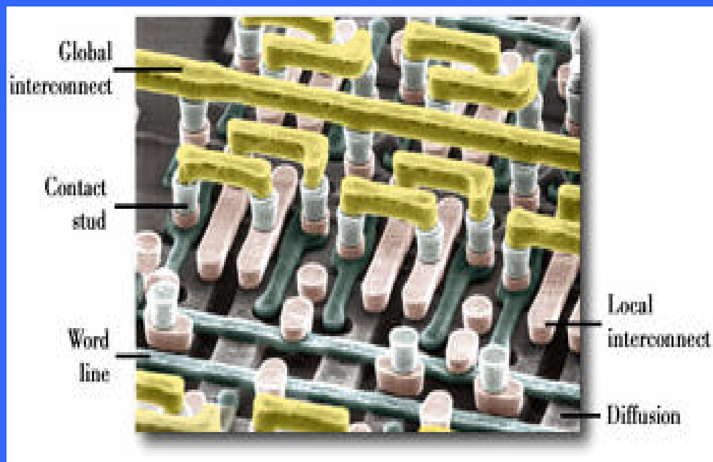
- Stresses due to epitaxial mismatch, phase changes, material densification, etc.
- Process variations,
- Material transport.

In addition, there are operating failures:

Thermal mismatch and the associated thermal stresses can cause fatigue and fracture.

The current densities carried by the wiring is rather large (10^4 A/cm^2) and the electron flow can sweep atoms out of the wire lattice and drive them towards the anode, causing voids at the cathode end and fracture at the anode. This is electromigration.



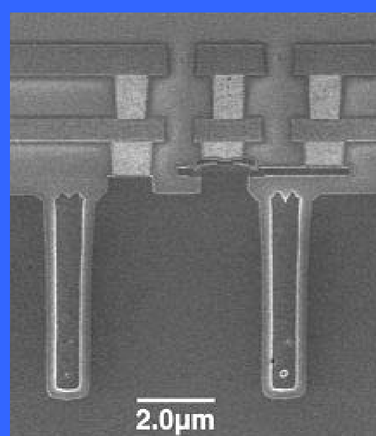


Failure analysis and metrology in these structures is a key technological challenge.

Goal

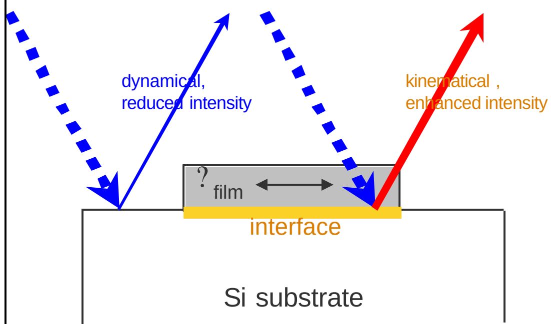
Fast, accurate, quantitative maps:

- Stress, strain, rotation
- Configuration/ geometry
- Chemical composition
- Phase distribution



SEM cross-section of SiGe HBT showing deep and shallow trench isolation with two levels of planar metal interconnection.

Microtopography

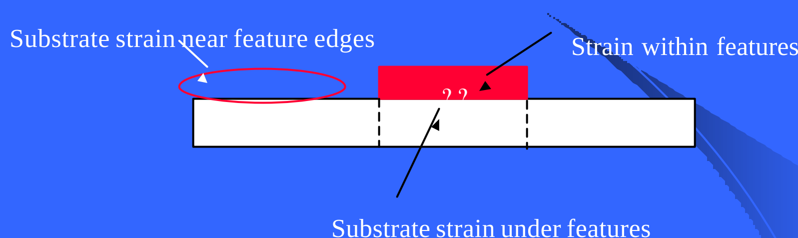


- Divergent beam..
- Patterns of metal (W, Ni, Cu, Al) dots.
- We map the intensity of a silicon reflection in the plane of the wafer.

-"Electromigration induced stress in aluminum conductor lines measured by x ray microtopography", Wang P.-C., Noyan I.C., Kaldor S. K., Jordan-Sweet J, Liniger E. G., Hu C.-K., Appl. Phys. Lett. Vol. 76, 2000, pp. 3726-3728

Wang P.-C., Noyan I.C., Kaldor S. K., Jordan-Sweet J, Liniger E. G., Hu C.-K., Appl. Phys. Lett. Vol. 78, 2001, pp. 2712-2714

Microtopography

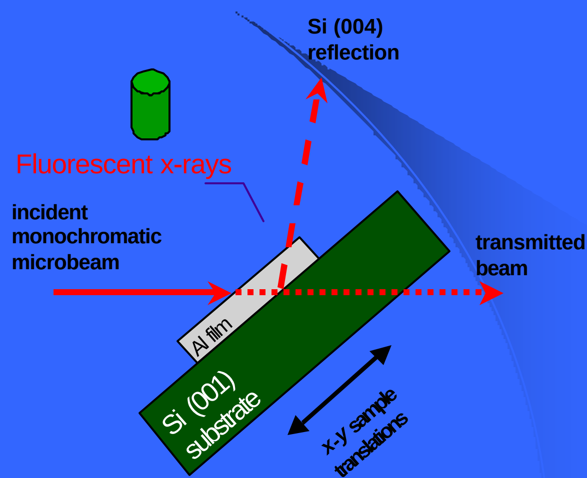


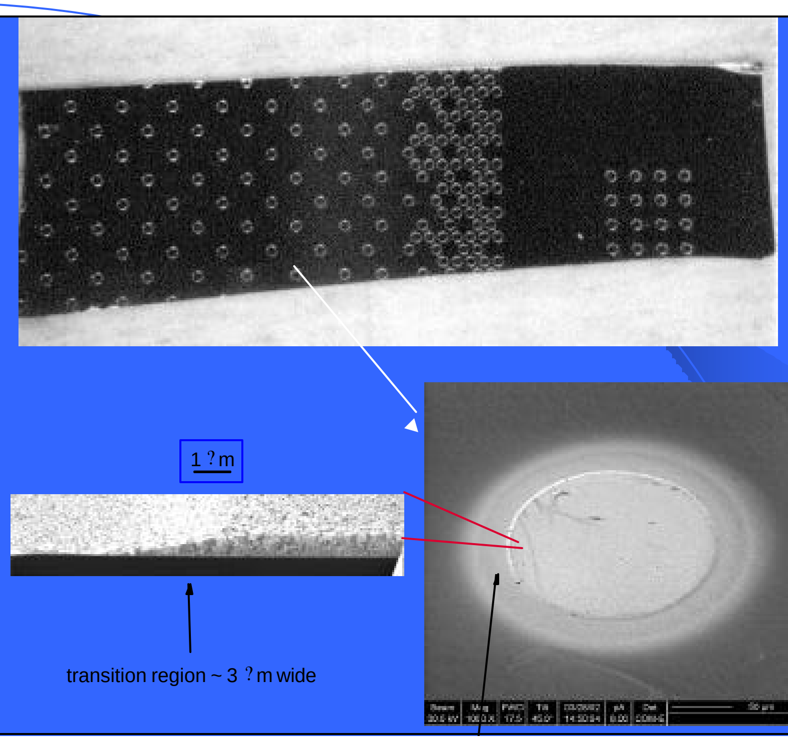
Synchrotron-based x-ray scanning topography:

- dynamic to kinematic transition in substrate diffracted intensity
- highly sensitive to minute strain gradients in single crystal substrates

We also map the fluorescent x-rays from the feature, and, thus, can locate its edge precisely.

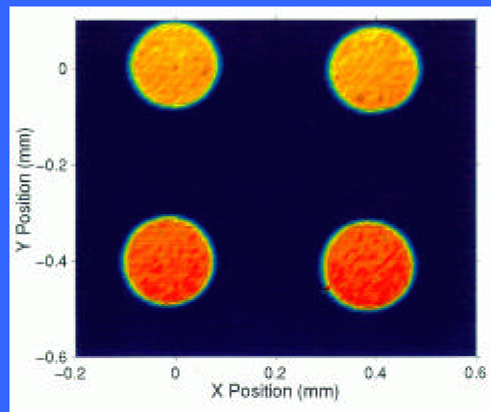
First set of experiments from X20-A beamline of NSLS.





The Ni-K? map from a Ni sample with 170 micrometer radius dot array.

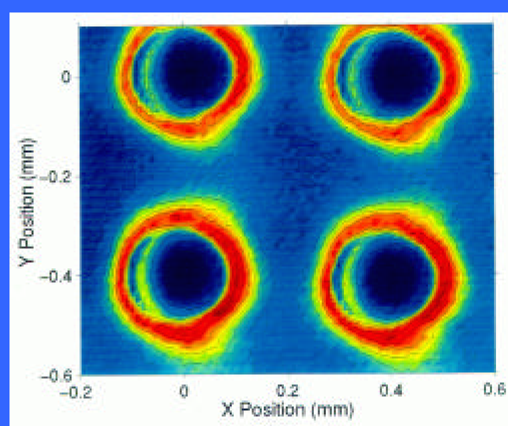
The dots are 1 micrometer thick, evaporated at ambient temperature on Si 111 type substrates.



The Si 333 reflection map from the same sample.

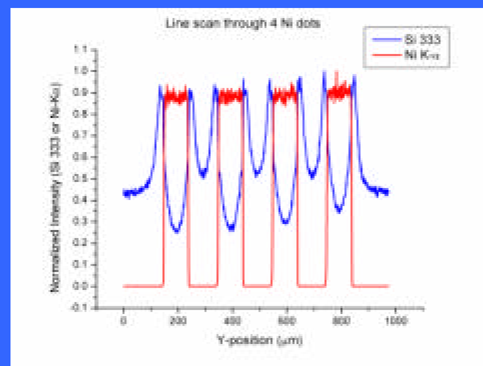
We observe enhanced intensity at the edges, which persists far away from the dots.

This shows the presence and extent of the shear fields.



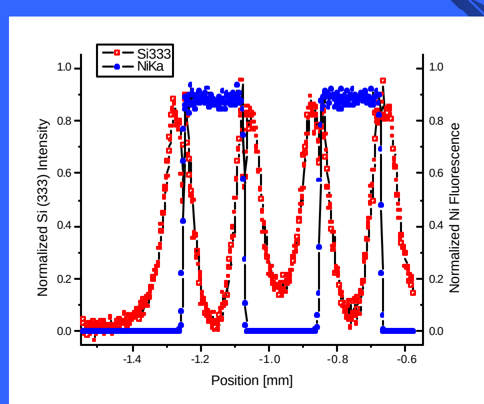
If we look at a cross-section through four dots, we observe:

- The shear maxima are at the edges. However, they are displaced out from the dot edge, which contradicts theory.
- Intensity is below the dynamical limit at the dot center.
- In regions between dots, the shear fields overlap.

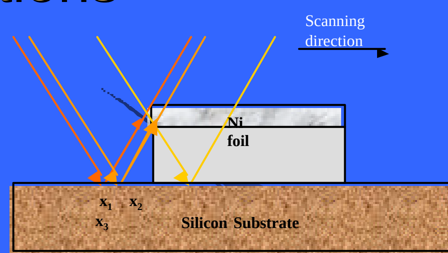


Enhanced Si (333) intensity

- Line scans of Si (333) vs. position confirm diffracted intensity increase due to strain
- Effects of Ni dot observed in Si substrate approximately 120 ?m away



Corrections



The previous slides contained raw data, which did not take into account the presence of absorption.

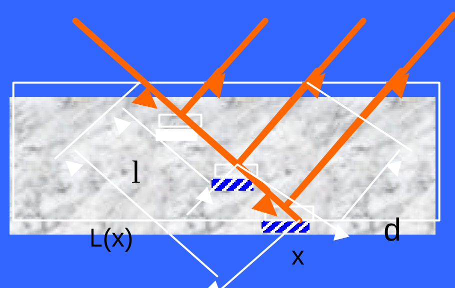
This effect was analyzed and corrected.

$$I(x) ? I_0 \int_0^? e^{??_f ?[f(x)? g(x?2z/\tan(?))]} G(z)dz$$

$$G(z)dz ? \frac{e^{???_s z/\sin(?)}}{\int_0^? e^{???_s z/\sin(?)}dz} dz$$

$$I(x,y) ? \iiint G(z)e^{??_f h(y?y_B)?[f(x?x_B)? g(x?x_B?2z/\tan(?))]} B(x_B, y_B)dx_B dy_B dz$$

Fluorescence



We assume the excitation of fluorescence on each block is proportional to the intensity of incident x-ray on that block, which is equal to

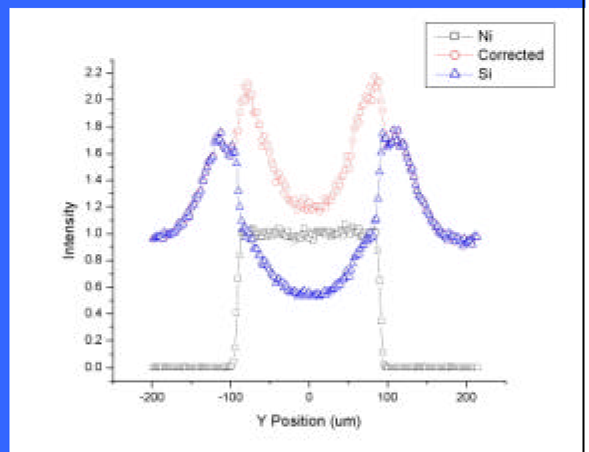
$$KI_0 e^{??_1 l}$$

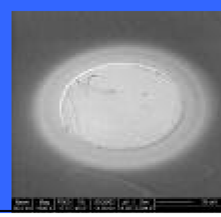
The excited fluorescence will be attenuated by a length d before it can emit from the surface, so the final expression is

$$I(x)_{Fluorescence} ? KI_0 \iiint_{L(x?x_B,y?y_B)} e^{?[?_1 l ??_2 d(l,x?x_B,y?y_B)]} ? B(x_B,y_B)dl dx_B dy_B$$

When the corrections are applied we obtain:

- The shear maxima are at the edge.
- There are two subsidiary maxima outside the edge.
- These are caused by a halo of Ni around the dot.

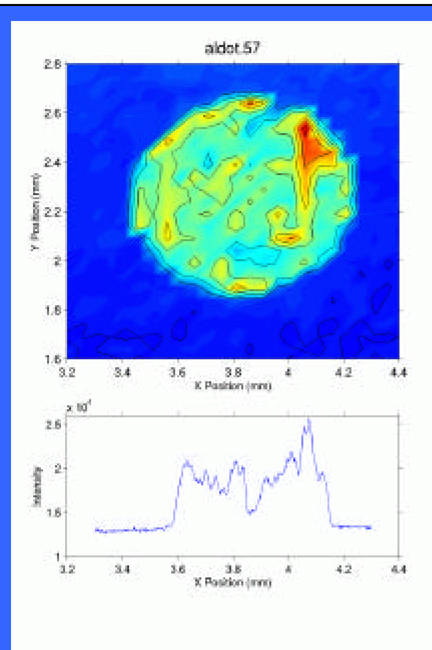




Microbeam topography can also be used to qualitatively identify interfaces.

Multiple shear maxima inside the dot indicate an "interrupted" interface.

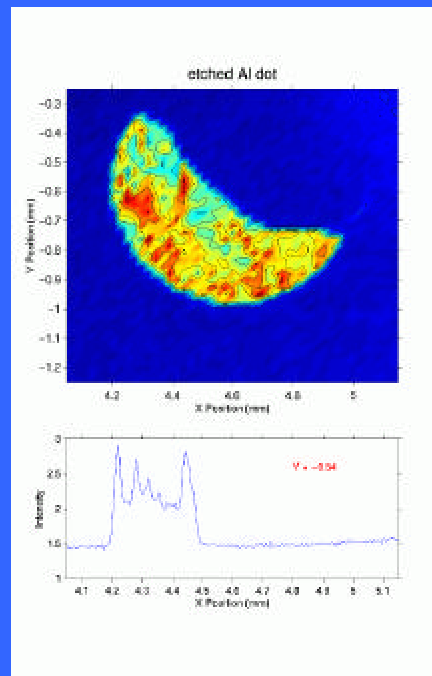
The average distance between the shear maxima describes the "critical adhesion length" of the interface.



The shear effects are purely elastic.

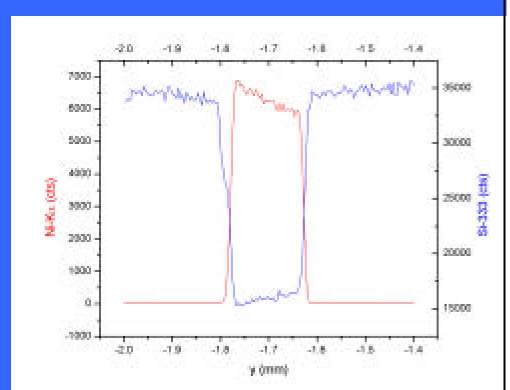
If the dot is etched, there is no remaining shear contrast in the case of Al.

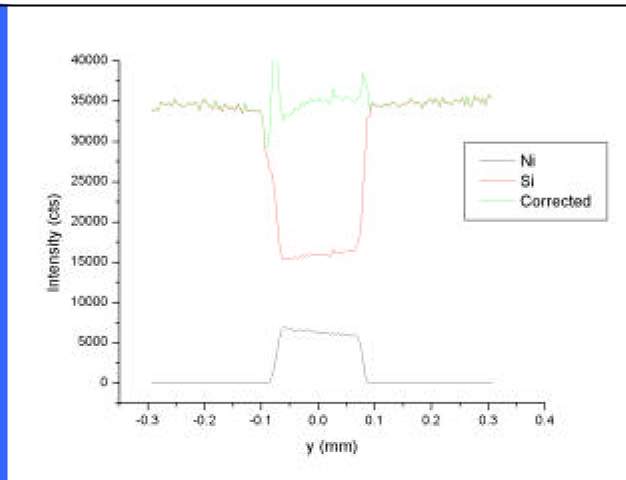
In the case of the Ni dots, the issue is more complicated.



If we etch the Ni dots, and map a dot that is still left on the surface, we see that most of the shear-peaks are removed.

If we correct the intensity for absorption, we see that there is still some adhesion.

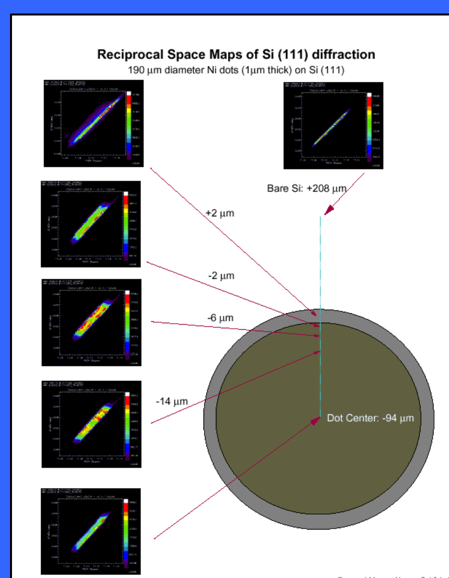


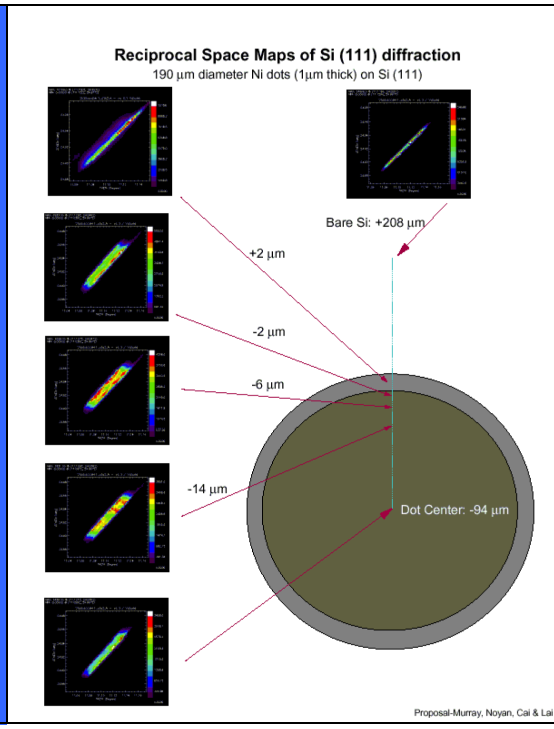


The edges still retain some degree of shear.

Full reciprocal-space mapping of the (un-etched) Ni dots revealed a “coherent” second layer near the edge.

Knowing the Si readily forms an epitaxial silicide with Ni, we looked for any evidence of this layer.





Etching studies revealed a “decorated” edge that was left behind after the Ni dots floated away.

Energy dispersive analysis confirmed that there was still Ni in the decorations.

In undecorated areas of the interior no Ni was found.

The decorations may be silicides, they show faceted topology.

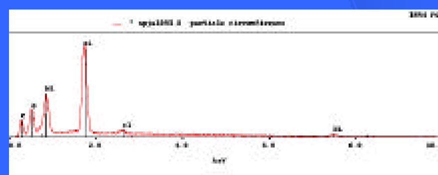
The native oxide also appears to be damaged.

This may be due to the high stress in the Ni films.

Measurement of the Ni stress using macro-beam techniques yielded an in-plane stress around 1 Gpa.

There will be a comparable shear stress at the edges.

This issue is under further study.



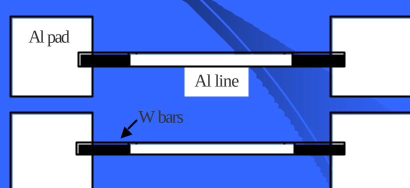
In-situ Electromigration Studies

The current densities flowing through interconnections exceed 25,000 A/cm2.

IR heat + heat generated during transistor cycles can cause local temperatures to exceed 100 °C.

At such current densities the electron flow biases atomic diffusion.

The atoms move downwind with the electron "wind", from cathode to anode.



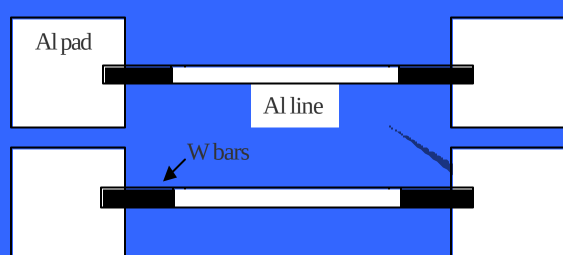
The material is removed from the cathode, creating excess vacancies and the formation of a "tensile" stress field.

These vacancies migrate together and form voids.

The electron wind piles up the atoms at the cathode.

This pile-up causes compressive stress to build up between the wire and the surrounding passivation.

For high currents, cracks form and the Al or Cu squeeze out of the wire.



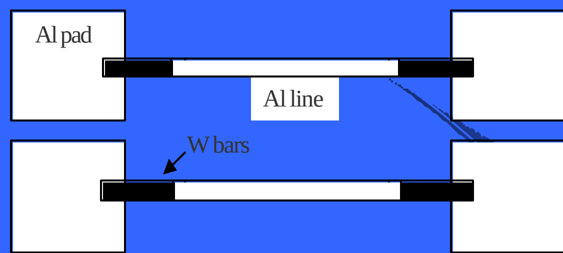
Passivated Al/0.25 at. % Cu

10? m wide, 0.5? m thick, 200 ? m long.

100 ^{o}A Ti/ 600 ^{0}A TiN shunt layer.

Sputter dep./RIE/ 400 ^{o}C anneal.

W bars @ ends block diffusion to pads.



1.5 mm thick passivation (SiO2)

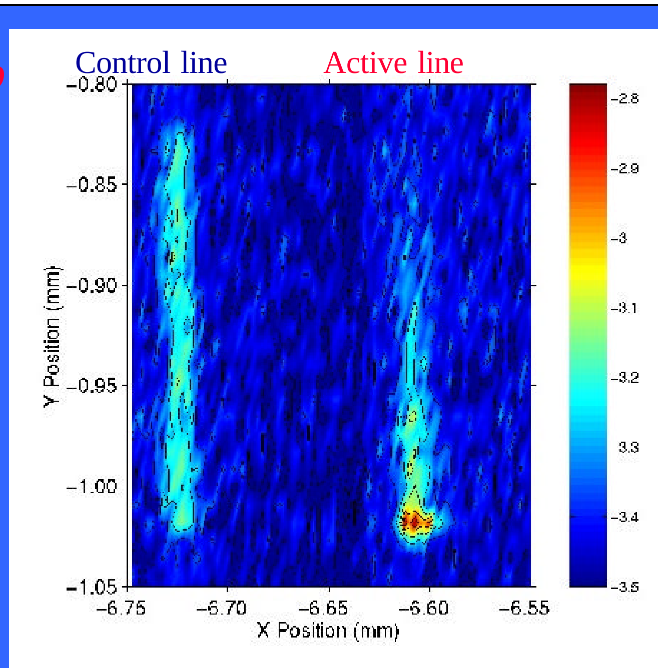
100,000 Amps/cm2, 302 ^{o}C.

We will also track the Cu flow through fluorescence mapping.

Cu-K? map

Cu distribution in the control line is ~ uniform.

Almost all Cu has migrated to the anode in the stressed line.

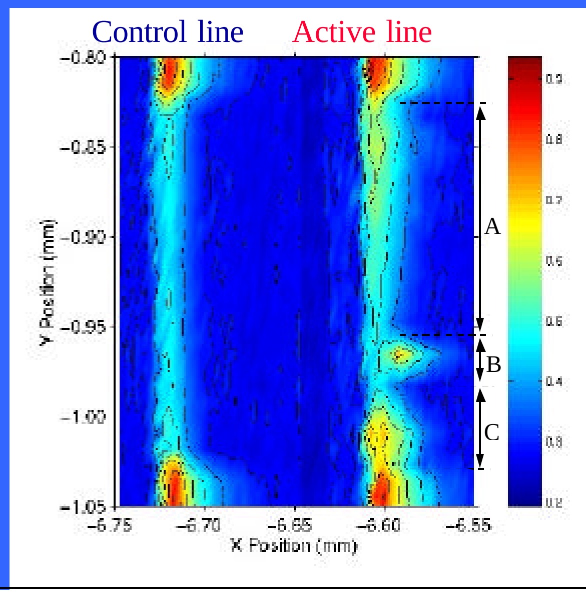


Si 004 topograph

Stress distribution in the control line is ~ uniform.

We observe intensity gradients in the stressed line indicating the formation of stress gradients..

There is an unexpected high stress region in region “B”.

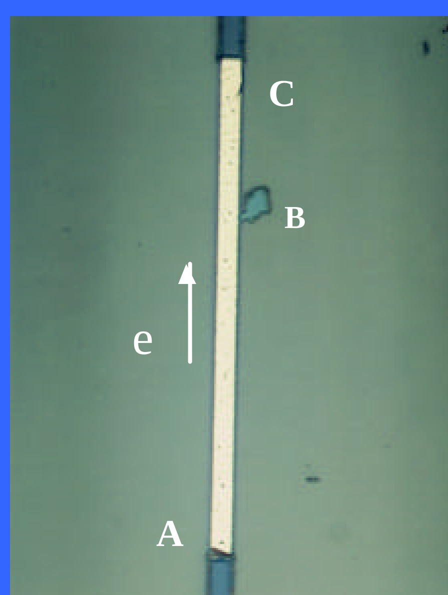


Optical microscopy indicated:

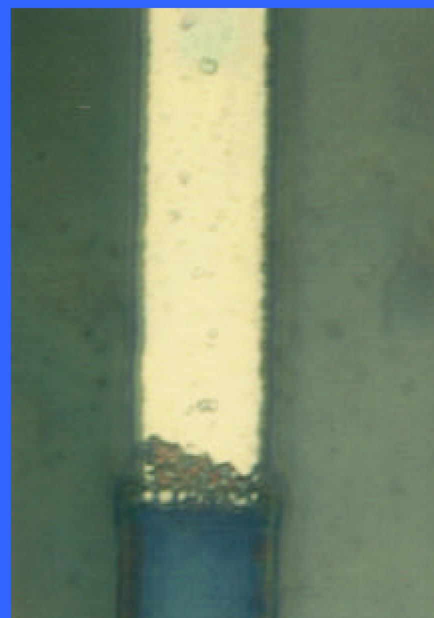
An extrusion @ B,

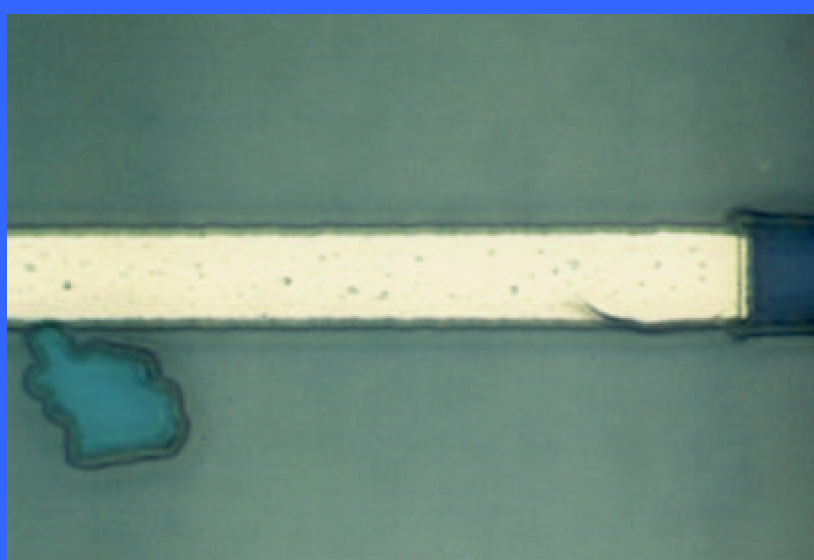
A depletion region at the cathode (A)

A crack at the anode (C)

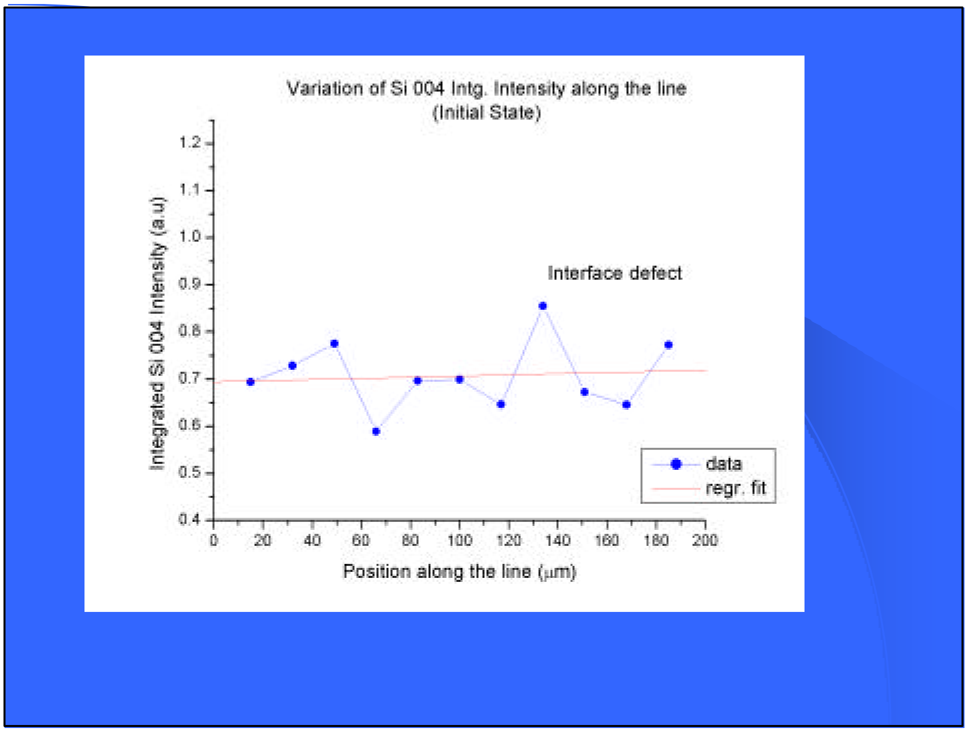


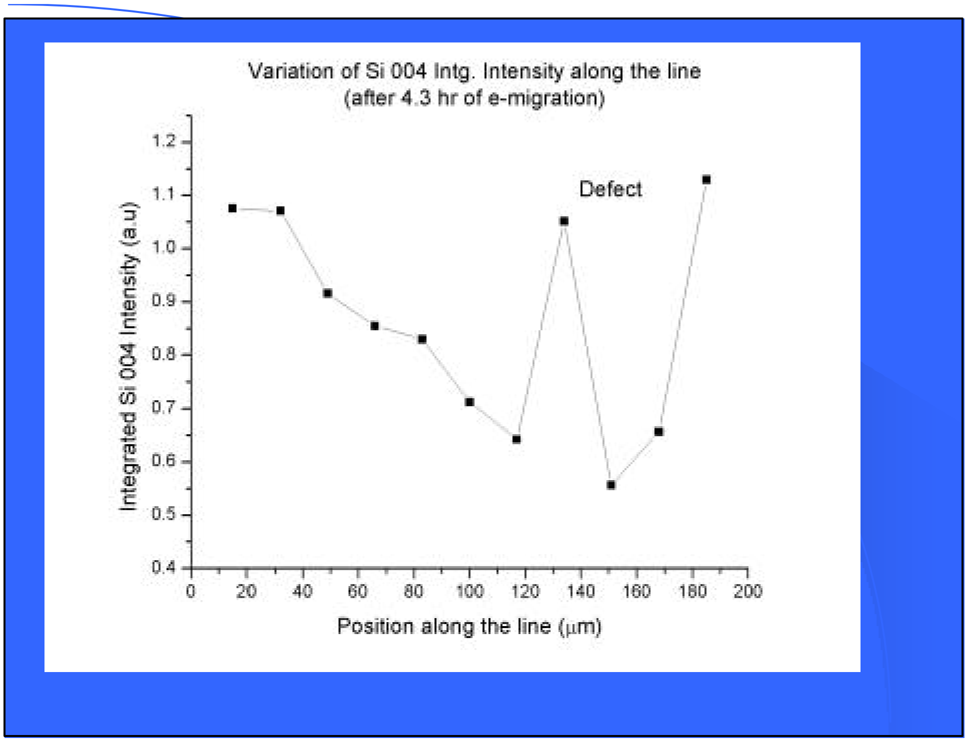
Anode-detail

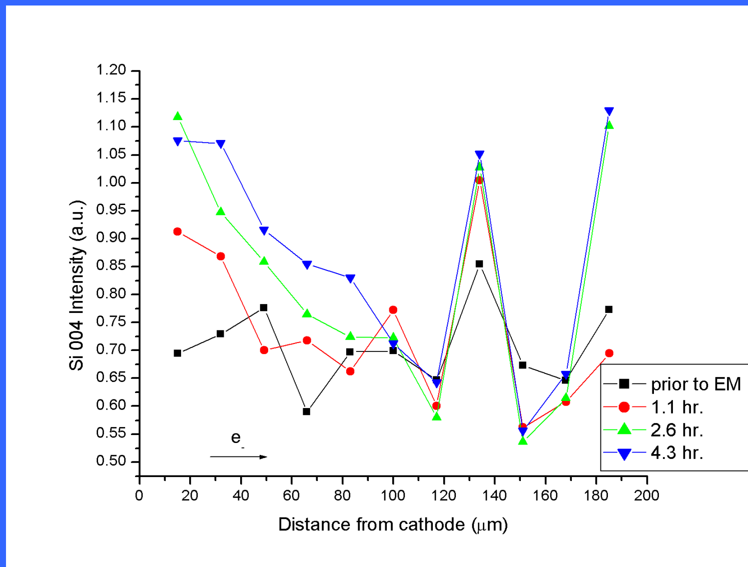




Regions B+C


Variation of Si 004 Intg. Intensity along the line
(Initial State)
Integrated Si 004 Intensity (a.u)
Interface defect
data
regr. fit
Position along the line (μm)


Variation of Si 004 Intg. Intensity along the line
(after 4.3 hr of e-migration)
Integrated Si 004 Intensity (a.u)
Defect
Position along the line (μm)

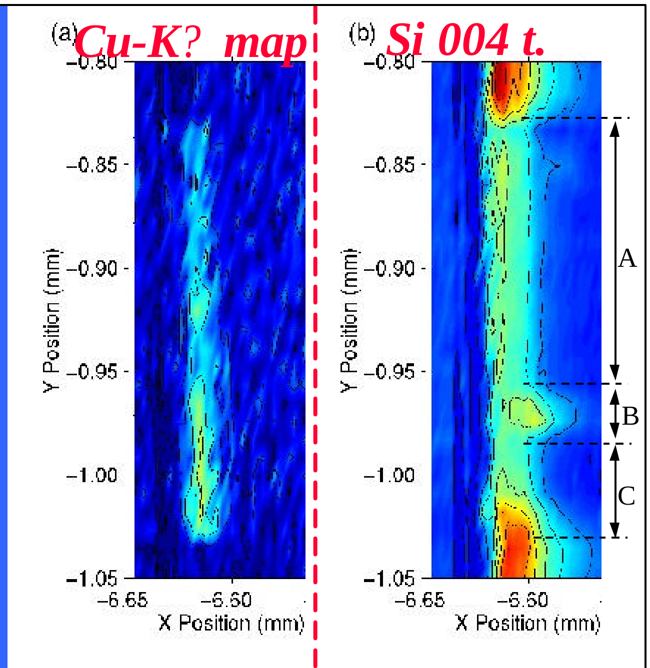


The extrusion formed @ a local defect.

If we turn off the current but leave the heat on, relaxation occurs.

•Cu flows back

•Stress becomes more uniform.



Si-Ge Strip Analysis

SiGe strips (100 microns long, 1 to 20 microns wide, ~.2 microns thick)

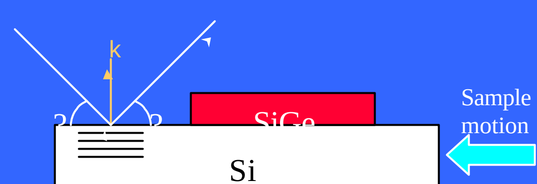
Etched from blanket films.

- Unprocessed
- Processed

Measurements

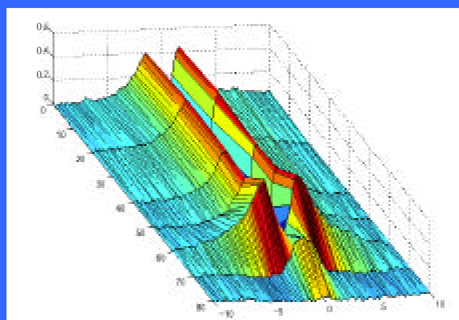
Conducted at APS 2ID-D

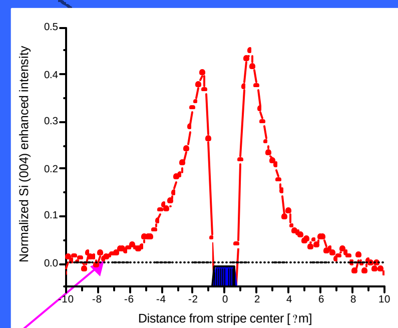
- UHV/CVD 0.24 ? m thick $Si_{0.86}Ge_{0.14}$ on Si (001)
- 100 ? m features etched (various widths)
- Fresnel zone plate optics, beam size ~ ????? m
- E = 9.2 keV
- Map Si (004) and SiGe (004) diffracted intensity



Experimental: 1.5 ? m SiGe feature on Si (001)

Normalized Si diffracted intensity [? I/I_0]





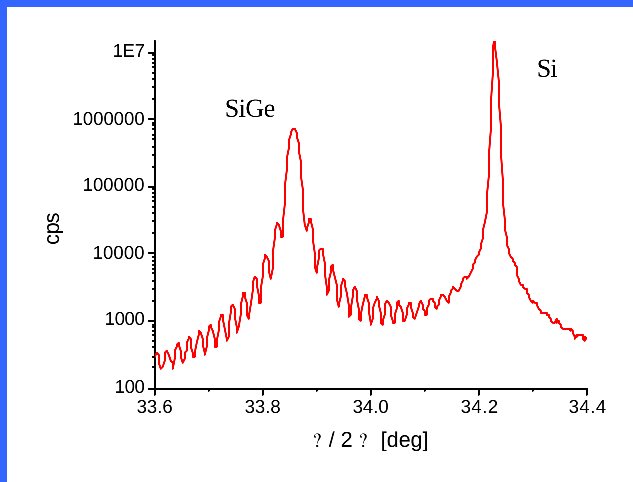
Distance from stripe center [? m]

- Distortion in Si substrate detected ~ 7 ? m away from stripe edge .
  - The smaller the beam size, the better the resolution.

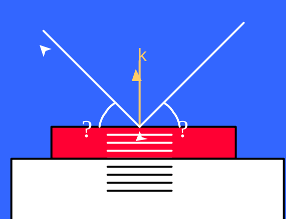
High-Resolution Microdiffraction

- Full reciprocal space mapping of single-crystal reflections.
- Necessary to resolve the epitaxial strain effects.
- Requires a parallel beam and analyzer crystal.

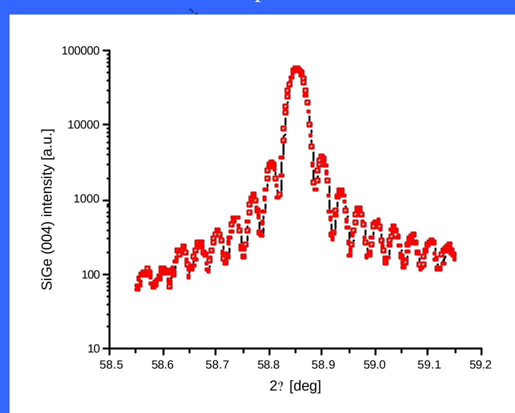
Blanket SiGe prior to etching



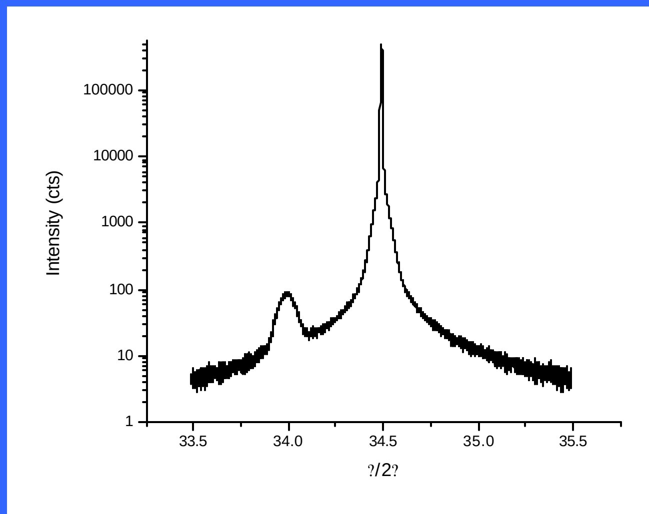
- ? / 2? scans at feature centers



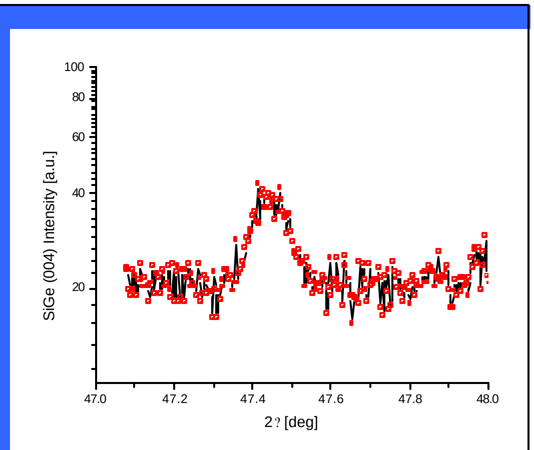
SiGe strip

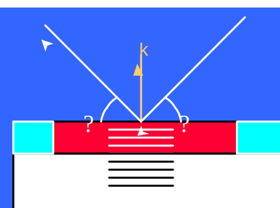


Bulk average of processed SiGe features



- ? / 2? scans at feature centers

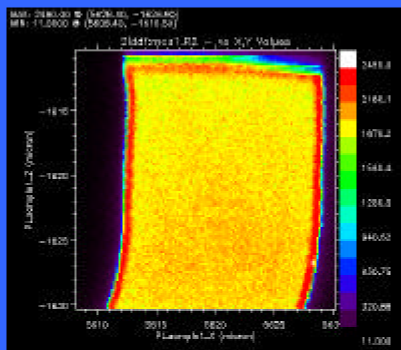


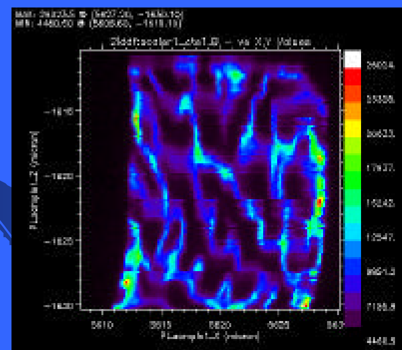


16 x 2048 ? m feature

Ge K? fluorescence

SiGe (004) diffracted intensity





The drift is due to temperature change.

Conclusions

– Topography-Fast, very sensitive to strain.
– We need to do topography, phase ID and high-resolution microdiffraction simultaneously!
– We also need to develop the equations that link intensity contrast to stress/strain.
– This probably qualifies as one or many “grand” challenge (s).
– It promises to be a fun exercise.

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